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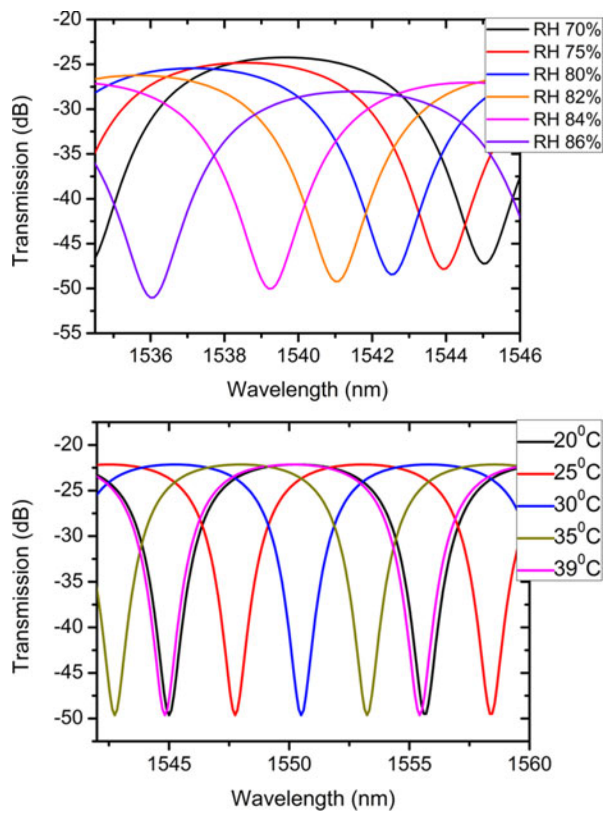
Lei Sun
Yuliya Semenova
Qiang Wu
Dejun Liu
Jinhui Yuan
Xinzhu Sang
Binbin Yan
Kuiru Wang
Chongxiu Yu
Gerald Farrell



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Investigation of Humidity and Temperature Response of a Silica Gel Coated Microfiber Coupler

Lei Sun,[1,2] Yuliya Semenova,[2] Qiang Wu,[1,3] Dejun Liu,[2] Jinhui Yuan,[1,4] Xinzhu Sang,[1] Binbin Yan,[1] Kuiru Wang,[1] Chongxiu Yu,[1] and Gerald Farrell[2]

[1]State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China
[2]Photonics Research Centre, Dublin Institute of Technology, Dublin 8, Ireland
[3]Department and Electrical Engineering, Northumbria University, Newcastle Upon Tyne 15 NE1 8ST, U.K.
[4]Photonics Research Centre, Department of Electronic and Information Engineering, The Hong Kong Polytechnic University, Hong Kong

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Corresponding author: J. Yuan (e-mail: yuanjinhui81@163.com).

Abstract: The humidity and temperature responses of a microfiber coupler (MFC) coated with silica gel are investigated. Two MFC structures with different waist diameters of 2.5 and 3.5 μm were fabricated by fusing and tapering two single-mode fibers using a microheater brushing technique. The influences of the coating thickness and tapered waist diameter on the sensing performance are analyzed. For the proposed sensor with a waist diameter of 2.5 μm and 8-layers thick coating, the change in the relative humidity (RH) results in an exponential blueshift with a maximum sensitivity of 1.6 nm/% RH in the range from 70 to 86% RH. In response to the temperature change, the sensor's transmission spectrum redshifts in a linear fashion with an average sensitivity of 0.55 nm/°C in the range from 20 to 40 °C. The study is important for the development of the proposed fiber structure as a humidity or temperature sensor.

Index Terms: Microfiber coupler, silica gel, humidity response, temperature response.

1. Introduction

Since the first report in 2003 [1], increasing research interest has been shown in optical microfiber/nanowire-based photonic devices. While maintaining the same advantages as conventional optical fibers, microfibers offer a number of outstanding optical and mechanical properties such as large evanescent field, strong light confinement, flexible configurability, and possibility of low-loss interconnections [2]–[4]. Microfibers/nanowires can tightly confine light to a very small area

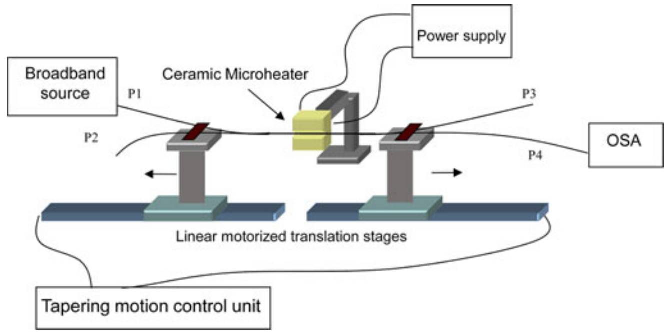

Fig. 1. Schematic diagram of the microfiber coupler fabrication setup.

and can deliver a considerable fraction of power propagating as an evanescent field, which in turn makes such structures sensitive to the surrounding medium [5]–[7].

Microfiber couplers have been successfully used in a range of sensing applications such as refractive index [8], humidity [9] and temperature [10] sensing, etc. Some examples include an MFC based humidity sensor with a polyethylene oxide coating [9] and a temperature sensitive MFC with a thermos-sensitive film overlay [10]. Unlike a microfiber where the environment influences a single evanescent field, the MFC used as a sensor relies on the environment influencing the coupling between two evanescent fields, which is more sensitive to the surrounding medium by comparison to the sensitivity of a single microfiber [11], [12]. In addition, the MFC displays a transmission dip due to the mode coupling so that in sensing applications, interrogation can be undertaken by detecting the dip wavelength shift [13], [14]. This is more reliable than interrogation using measurements of the transmitted power variation, which is necessary when sensing is undertaken by means of a single microfiber.

Silica gel is a kind of transparent material whose porosity and inner structure are affected by humidity, leading to the dependence of its equivalent refractive index on the humidity [15]. A silica gel coated MFC therefore is a good candidate for high sensitivity humidity sensing. In addition, silica gel solutions can be easily coated on the surface of optical fibers due to its moderate viscosity and the match between the silica gel and the optical fiber core, which are made of the same silica material [16].

In this paper, we investigate the temperature and humidity response of a silica gel coated MFC for the first time. Experimental results show that the temperature and humidity sensitivities of the MFC can be enhanced by increasing the coating thickness or decreasing the MFC waist diameter. The spectral dip wavelength shifts exponentially as the RH varies from 70 to 86%. A maximum sensitivity is estimated as 1.6 nm/% RH in the RH range of 84 to 86%. The spectral dip wavelength experiences a linear redshift with the increase of temperature. A maximum sensitivity of 0.55 nm/°C is achieved. In addition, the good linearity of the wavelength shift versus surrounding temperature change offers the possibility of a straightforward temperature correction scheme.

2. Microfiber Coupler and Experiment

2.1. Microfiber Coupler Fabrication

The MFC was fabricated by tapering and fusing two fibers together at the same time with the microheater brushing technique [17]. Fig. 1 shows a schematic diagram of the fiber tapering set-up. Two standard single-mode fibers (SMF-28, Corning, NY, USA) were slightly twisted together to guarantee that the two fibers stayed in contact during the tapering process. Then the two fibers were fixed on two linear translation stages whose motion was precisely controlled by means of the specially developed software program. A ceramic microheater (CMH-7019, NTT-AT) was used to heat up the fibers to circa 1300 °C, and the combination of heating and stretching of the fibers formed a tapered structure. Two MFC sensor samples with tapered waist diameters of 2.5 μm and

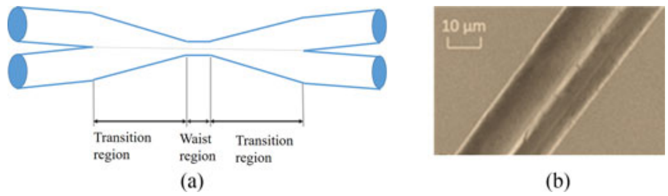

Fig. 2. (a) Schematic diagram of an MFC. (b) SEM image of an MFC sample.

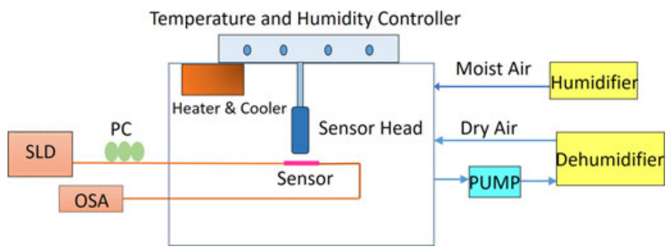

Fig. 3. Experimental set-up used for the temperature and RH measurements.

3.5 μm were fabricated. The two sensor samples are referred to as M-2.5 and M-3.5, respectively. Fig. 2(a) shows the schematic diagram of the MFC structure. For each sensor, the fabricated MFC had a total length of 25 mm which includes a 3 mm long uniform waist region at the center and two 11 mm long transition regions at each end. Fig. 2(b) shows a partial SEM image of one of the MFC samples. From Fig. 2(b), it can be seen that the two microfibers are weakly fused together, offering a higher sensitivity to environmental changes compared with the strongly fused fibers [18].

2.2. Silica Gel Preparation and Coating

The silica sol solution is an optically transparent glasslike material, which was prepared as follows. 10 ml of tetraethylothosilicate (TEOS) was mixed with 5 ml of ethanol for 20 minutes using a magnetic stirrer, and subsequently, 1 ml of 0.1 mol/L H_2SO_4 solution was added and mixing continued for further 100 minutes.

Both sensor samples were fabricated by passing the MFC through a small container with the prepared silica gel using a controlled motorized translation stage. Single-layer coating involves passing the silica gel source from the one end of the MFC to the other end. Previous reports have shown that for other (non-MFC) types of fiber sensors, increasing the thickness of a coating layer on the fiber surface can increase sensitivity to a target measurement [19]. Thus, by repeating the single-layer coating process, different silica coating thicknesses can be built up. The motorized translation stage could ensure that each single-layer coating was applied with the same coating condition, which contributed to the coating uniformity along the taper fiber and same coating thickness of each layer. It is noted that each coating layer was left to dry for 15 minutes before the next coating was applied. In our work, to investigate the impact of the coating thickness, the sample sensor with 2.5 μm diameter was coated with 3-layers and 8-layers, respectively.

2.3. Experimental Set-Up

Fig. 3 shows the experimental set-up for the sensor characterization. The system consists of a broadband light source (Fiber Coupled SLD, Thorlabs), polarization controller (PC), optical spectrum analyzer (OSA) (86142B, Agilent), and a temperature/humidity controlled chamber (ETS 5003). Relative humidity within the chamber can be controlled in the range of 50–90% RH and temperature in the range of 20–50 °C. Each temperature and humidity measurement was recorded five minutes

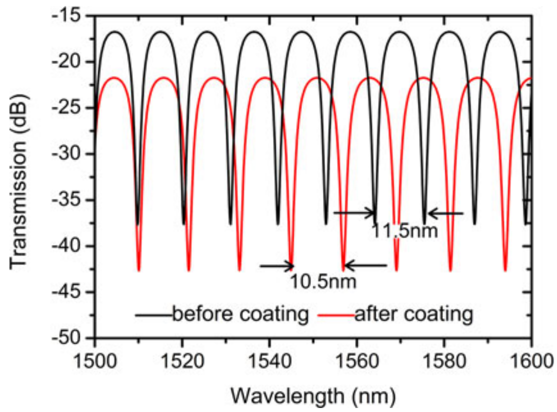

Fig. 4. Transmission spectrum before and after silica gel coating.

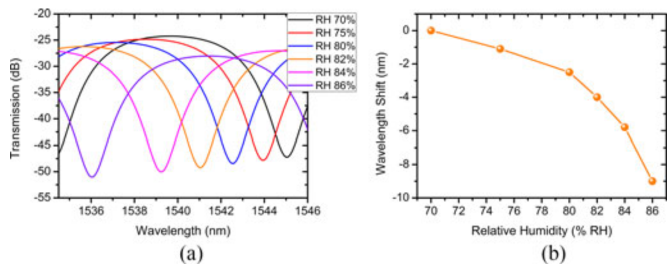

Fig. 5. (a) Transmission spectra of the coated MFC at different relative humidity values. (b) Measured wavelength shift versus relative humidity.

after each value was set to ensure the temperature and humidity in the chamber stabilized. An independent electronic probe was used to monitor the actual temperature and humidity in the chamber as a reference.

3. Result and Discussion

Fig. 4 shows the transmission spectra of the uncoated M-2.5 sample sensor and after 8-layers of the silica gel coating were applied to its surface. As expected, the transmission spectrum displays a series of spectral dips, due to the mode interference over the taper length. The application of silica gel causes a decrease in the coupler free spectral range from 11.5 to 10.5 nm because the refractive index of the silica gel modifies the mode interference conditions for the two fused microfibers within the MFC. In addition, an increased optical loss was observed due to the larger scattering loss at the surface of the MFC after coating with the silica gel.

To investigate the humidity dependence of such a sensor, the temperature was set at a constant value of 20 °C in the chamber. Even though decreasing the tapered diameter can increase the sensor's sensitivity, the smaller taper diameter makes the MFC more difficult to handle and more importantly the free spectral range will be reduced correspondingly, which decreases the detection range. Taking into consideration of the trade-off between the sensitivity, detection range, and the stability of the proposed sensor, the diameter of 2.5 μm was selected for our experiments. Fig. 5(a) shows the spectral response of the M-2.5 sample sensor at different RH values for the MFC coated with 8-layers of silica gel. It is observed that the wavelength of spectral dips is blue-shifted monotonically as the RH increases from 70 to 86% RH. This phenomenon can be explained by the fact that when the surrounding RH increases, the water vapor content of the air in contact with the coating increases thus causing an increase in the diffusion of water molecules into the coating

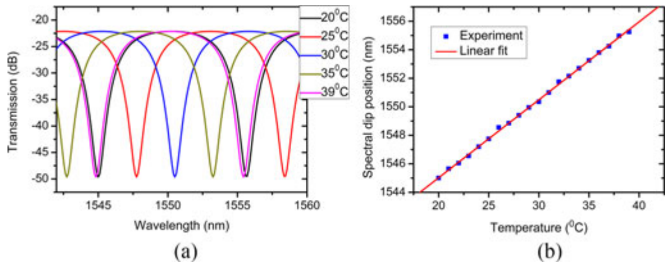

Fig. 6. (a) Transmission spectra of the coated MFC at different temperatures. (b) Spectral position of selected spectral dip versus temperature.

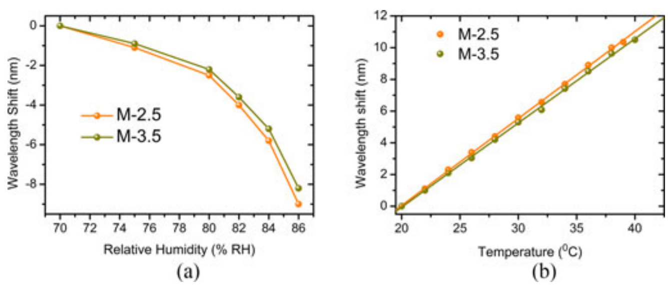

Fig. 7. Wavelength shifts for the two different tapered sample sensors: M-2.5 and M-3.5. (a) In response to humidity and (b) in response to temperature.

which are absorbed by the gel surface [20]. As the silica gel coating absorbs more water from the environment this in turn gives rise to an increase in the effective refractive index of the coating. It is well known that the MFC spectrum undergoes a blueshift when the surrounding refractive index increases [21]. The wavelength shift versus RH change is presented in Fig. 5(b). It is obvious that the dip wavelength shift has an exponential relationship with the RH change. The total wavelength shift is 9 nm when the RH varies from 70 to 86%, and the maximum sensitivity of 1.6 nm/% RH is achieved in the RH range of 84 to 86%.

In order to study the sensitivity to temperature for the proposed sensor at a constant humidity, we used the same sample sensor as in the above humidity experiment: M-2.5 sample with an 8-layer silica coating. During the test, the humidity was set at a constant value of 50% RH (chosen as it is a typical mid-range humidity value) in the chamber and the temperature was gradually raised from 20 to 40 °C. Fig. 6(a) shows several transmission spectra for the MFC coated with 8-layers of silica gel at different temperatures, and Fig. 6(b) illustrates the spectral shift of a selected spectral dip versus temperature. It can be seen that the coupler's spectrum exhibits a linear redshift with temperature with an average sensitivity of $\sim$0.55 nm/°C in the temperature range of 20 to 39 °C. This is likely due to the fact that increasing temperature stimulates water molecules desorbing into the vapor phase [22], which results in a decrease of the refractive index of the silica gel.

It is known that the sensitivity of an MFC to the local environment depends on the tapered waist diameter. However, if the change in the sensitivity due to the tapered diameter is high, this will present problems with repeatability when fabricating many devices on a larger scale. In order to investigate the influence of fabrication error on the sensitivity of the proposed senor, two tapered waist diameters of 2.5 μm (M-2.5) and 3.5 μm (M-3.5) were selected in the experiments. This allows fabrication error of $\pm$0.5 μm for a fiber taper waist of 3 μm, which is reasonable for most optical fiber tapering systems. Using the M-2.5 and M-3.5 sample sensors, we carried out a series of experiments to investigate the dependence of both humidity and temperature sensitivities on the tapered waist diameter. Both sensor samples had 8-layers of silica gel coating. Figs. 7(a) and 7(b) show the wavelength shifts versus the humidity and temperature changes, respectively, for the

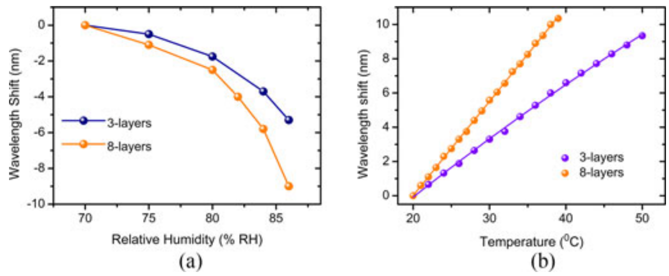

Fig. 8. (a) Measured wavelength shift versus humidity for different coating thicknesses. (b) Measured wavelength shift versus temperature for different coating thicknesses.

M-2.5 and the M-3.5 samples. As seen from Fig. 7(a), the humidity sensitivity increases marginally as the tapered waist diameter decreases, and the same phenomena can also be observed for the temperature sensitivity, as shown in Fig. 7(b). This could be explained by the fact that the sensor with a smaller waist diameter has a larger portion of transmitted light energy within its evanescent field and thus there is a more efficient interaction with the surrounding environment. Thus, the change in the refractive index of the ambient material has a greater effect on the wavelength shift. However, the decrease in humidity sensitivity, which is induced by the increase in the tapered waist diameter from 2.5 to 3.5 μm (a diameter change of 40%) at an RH of 82%, is only about 6% at a temperature of 35 °C. In contrast, the decrease in temperature sensitivity is about 7% when the diameter change is 40% under the same temperature. It can thus be concluded that while the MFC tapered diameter does influence the sensitivity, this influence is low, which indicates that the sensor design is relatively insensitive to tapered diameter, which bodes well for ease of fabrication.

To investigate the impact of the coating thickness, we carried out a series of experiments for the M-2.5 sample sensor. Fig. 8(a) shows the measured wavelength shift of the M-2.5 sample sensor with two different coating thicknesses (3-layers and 8-layers coating) for different relative humidity values. The results show that a thicker silica gel coating leads to a larger wavelength shift. For the thicker coating thickness, the change of the refractive index of the gel is stronger, so the sensitivity is higher. The wavelength shifts are 5.3 and 9 nm, respectively, when the environmental humidity changes from 70 to 86%, which show that the sensitivity of 8-layers coated sensor is better than that of 3-layers coated sensor. This result indicates that it is possible to control the inherent sensitivity of the sensor by controlling the coating thickness.

Fig. 8(b) shows the measured wavelength shift of M-2.5 sample sensor with two different coating thicknesses (3-layers and 8-layers) at different temperatures. When the temperature increases, for the sensor with a thicker coating, more water molecules will be desorbed from the silica gel, leading to a larger wavelength shift compared to that of the sensor with a thinner coating. The results indicate that the coating thickness influences both sensitivity to humidity and temperature. It is worth noting that temperature response shows good linearity. The linear temperature dependence is very important for developing the temperature correction scheme when the proposed device is used for humidity sensing in variable temperature environments.

4. Conclusion

In summary, the humidity and temperature responses of the proposed sensor based on the silica gel coated microfiber coupler are demonstrated. The change in the refractive index of the silica gel coating induced by the changes in the surrounding relative humidity and temperature lead to a spectral shift of the sensor's transmission. Both the relative humidity sensitivity and temperature sensitivity are influenced by the MFC waist diameter and the coating thickness, but the influence of the tapered waist diameter is less significant, which is useful as it points to relaxed tolerances for device fabrication. This study offers a prerequisite to the development of a temperature or humidity sensor based on the proposed fiber structure.

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